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► To cite this version:

Julien Bensmail, Foivos Fioravantes, Fionn Mc Inerney, Nicolas Nisse. The Largest Connected Subgraph Game. WG 2021 - The 47th International Workshop on Graph-Theoretic Concepts in Computer Science, Jun 2021, Warsaw, Poland. pp.296-307, 10.1007/978-3-030-86838-3_23 . hal-03219636

HAL Id: hal-03219636

<https://inria.hal.science/hal-03219636>

Submitted on 6 May 2021

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The Largest Connected Subgraph Game[★]

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Abstract. We introduce the *largest connected subgraph game* played on an undirected graph G . In each round, Alice colours an uncoloured vertex of G red, and then, Bob colours an uncoloured vertex blue, with no vertices initially coloured. Once all the vertices are coloured, Alice (Bob, resp.) wins if there is a red (blue, resp.) connected subgraph of order greater than the order of any blue (red, resp.) connected subgraph. If neither player wins, it is a draw. We first prove that Bob can never win, and define a large class of graphs (*reflection graphs*) in which the game is a draw. We show that determining the outcome of the game is PSPACE-complete in bipartite graphs of small diameter, and that recognising reflection graphs is GI-hard. We prove that, the game is a draw in paths if and only if the path has even order or at least 11 vertices, and Alice wins in cycles if and only if the cycle is of odd order. We also give an algorithm computing the outcome of the game in cographs in linear time.

Keywords: Games on graphs, Scoring games, Connection games, PSPACE-complete.

1 Introduction

Games where players strive to make connected structures are *connection games*. Several of these games are well-known, like the game of *Hex*, introduced by Hein in 1942, and independently by Nash in 1948 [9]. Hex is played by two players on a hexagon-tiled board with two of its opposing sides coloured red and the other two blue. Each round, the first player colours an uncoloured tile red, and then, the second player colours one blue. The player that connects the two sides with his color wins. Another famous connection game is the *Shannon switching game*, invented by Shannon in the 1950s [10]. In this game, the first player wants to connect two marked vertices in a graph, and the second player wants to prevent this. The players take turns selecting edges of the graph, and the first player wins if there is a path consisting of only his edges between the two marked vertices. A variant where the players select vertices (and obtain their incident edges) also

[★] This work has been supported by the European Research Council (ERC) consolidator grant No. 725978 SYSTEMATICGRAPH, the STIC-AmSud project GALOP, the PHC Xu Guangqi project DESPROGES, and the UCA^{JEDI} Investments in the Future project managed by the National Research Agency (ANR-15-IDEX-01). See [2] for the full version of the paper.

exists. However, not all connection games involve connecting sides of a board or two vertices in a graph. For example, in *Havannah*, a board game invented by Freeling in 1981, the players may also win by forming closed loops, with the board and the rules similar to Hex. Connection games tend to be difficult complexity-wise, which is a main reason they are played and studied. For example, Reisch proved that generalised Hex is PSPACE-complete [14], Even and Tarjan proved that the Shannon switching game on vertices (players select vertices, not edges) is PSPACE-complete [8], and Bonnet et al. proved that (generalised) Havannah is PSPACE-complete [3]. That being said, the Shannon switching game on edges is polynomial-time solvable [5]. For more on connection games, see [3,4].

Games in which the player with the largest *score* wins, are *scoring games*. The score in these games is an abstract quantity usually measured in a unit called *points*. Players may gain points in a myriad of ways, all depending on the rules of the game. For example, in the orthogonal colouring game [1], each player gets one point for each coloured vertex in their copy of the graph, and a player's final score is their total number of points. Recently, the papers [11,12] started to build a general theory around scoring games, and there have been many papers on different scoring games, such as [7,13,16]. In this paper, we introduce the following 2-player game that links connection and scoring games on graphs. For any graph G , the *largest connected subgraph game* is played between the first player, *Alice*, and the second player, *Bob*. Initially, no vertices are coloured. In each round, Alice first colours an uncoloured vertex of G red, and then, Bob colours an uncoloured vertex blue. Each vertex can only be coloured once and its colour cannot be modified. The game ends when every vertex in G is coloured. If there is a connected red (blue, resp.) subgraph whose order (number of vertices) is strictly greater than the order of any connected blue (red, resp.) subgraph, then Alice (Bob, resp.) wins. If the order of the largest connected red subgraph equals the order of the largest connected blue subgraph, then the game is a draw.

We first define notations and prove preliminary results for the largest connected subgraph game in Sec. 2, *i.e.*, showing that Bob never wins, that the game is a draw in a large class of graphs we call *reflection graphs*, and that recognising reflection graphs is GI-hard. In Sec. 3, we prove that the game is PSPACE-complete in bipartite graphs of diameter 5. We then study the game in particular graph classes, with the resolution of the game for paths and cycles in Sec. 4, and a linear-time algorithm for solving the game in cographs in Sec. 5. These graph classes interestingly illustrate different types of playing strategies that Alice and Bob can employ. Lastly, we finish with open questions in Sec. 6.

2 Notations and First Results

In this section, we define notations and give preliminary results for the game. For any graph G , if Alice (Bob, resp.) has a winning strategy in the largest connected subgraph game, then G is *A-win* (*B-win*, resp.). If neither Alice nor Bob has a winning strategy in the largest connected subgraph game, *i.e.*, it is a

draw if both players use optimal strategies, then G is *AB-draw*. Since it is never a disadvantage to play an extra turn, by the classic strategy stealing argument:

Theorem 1. [2] *There does not exist a graph G that is B -win.*

Since there are no B -win graphs, the next natural question to ask is whether there are A -win (AB -draw, resp.) graphs. There are an infinite number of A -win graphs as any star is A -win (Alice first colours the universal vertex). This also shows that there are an infinite number of graphs for which the order of the largest connected red subgraph is arbitrarily bigger than that of the blue one. There are also an infinite number of AB -draw graphs, since any graph of even order with two universal vertices is AB -draw. In Section 4, we show that any path of order at least 10 is AB -draw, and hence, that there are an infinite number of graphs of odd order that are AB -draw. We can actually define a much richer class of AB -draw graphs. A *reflection graph* is any graph G , whose vertices can be partitioned into two sets $U = \{u_1, \dots, u_n\}$ and $V = \{v_1, \dots, v_n\}$ such that:

1. there is an isomorphism between the subgraph induced by U and the subgraph induced by V , where v_i is the image of u_i , for all $1 \leq i \leq n$;
2. for any two vertices $u_i \in U$ and $v_j \in V$, if $u_i v_j \in E(G)$, then $u_j v_i \in E(G)$.

Theorem 2. [2] *Any reflection graph G is AB -draw.*

Indeed, a drawing strategy for Bob is to colour v_i (u_i , resp.), whenever Alice colours u_i (v_i , resp.). Any even-order graph that is a path, cycle, or Cartesian product of two graphs, is a reflection graph. We prove that recognising reflection graphs is not in P unless the Graph Isomorphism problem is:

Theorem 3. [2] *Given a graph G , deciding if G is a reflection graph is GI-hard.*

3 Complexity

In this section, we show that the largest connected subgraph game is PSPACE-complete, even in bipartite graphs of small diameter. Our reduction is via POS CNF, which was shown to be PSPACE-complete in [15], and is as follows:

POS CNF: 2-player game whose input is a set of variables $X = \{x_1, \dots, x_n\}$ and a conjunctive normal form (CNF) formula ϕ consisting of clauses C_1, \dots, C_m comprised of variables from X in their positive form. In each round, the first player, Alice, sets a variable (that is not yet set) to true, and then, the second player, Bob, sets a variable (that is not yet set) to false. Once each variable has been assigned a truth value, Alice wins if ϕ is true, and Bob wins if ϕ is false.

Theorem 4. *Given a graph G , deciding if G is A -win is PSPACE-complete, even if G is bipartite and has a diameter of 5.*

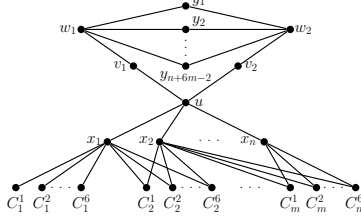


Fig. 1. An example of the construction of the graph G in the proof of Theorem 4, where, among other variables, the clause C_1 contains the variable x_1 , the clause C_2 contains the variables x_1 and x_2 , and the clause C_m contains the variables x_2 and x_n .

Proof. Since the number of rounds is $\lceil |V(G)|/2 \rceil$ and there are at most $|V(G)|$ possible moves for a player in any round, the problem is in PSPACE. To prove it is PSPACE-hard, we give a reduction from POS CNF. By adding a dummy variable, POS CNF remains PSPACE-hard if the number of variables n is odd. From an instance ϕ of POS CNF where n is odd, we construct, in polynomial time, an instance G of the largest connected subgraph game such that Alice wins in ϕ if and only if G is A -win. Let x_1, \dots, x_n be the variables and let C_1, \dots, C_m be the clauses in ϕ . The construction of G is as follows (see Figure 1 for an illustration): for each variable x_i ($1 \leq i \leq n$), there is a vertex x_i , and for each clause C_j ($1 \leq j \leq m$), there are 6 vertices C_j^1, \dots, C_j^6 . For all $1 \leq i \leq n$ and $1 \leq j \leq m$, if the variable x_i appears in the clause C_j , then there is the edge $x_i C_j^q$ for all $1 \leq q \leq 6$. Also, there are the vertices u, v_1, v_2, w_1, w_2 , and y_1, \dots, y_{n+6m-2} , and the edges $w_1 v_1, v_1 u, u v_2$, and $v_2 w_2$. Lastly, for all $1 \leq i \leq n$, there is the edge $u x_i$, and, for all $1 \leq \ell \leq n + 6m - 2$, there are the edges $w_1 y_\ell$ and $w_2 y_\ell$. To simplify the proof, let P be the subgraph of G induced by the vertices x_i ($1 \leq i \leq n$) and C_j^q ($1 \leq q \leq 6$ and $1 \leq j \leq m$), and let Q be the subgraph of G induced by the vertices $V(G) \setminus (V(P) \cup \{u\})$.

First, we prove that, if Alice wins in ϕ , then G is A -win. We give a winning strategy for Alice. In what follows, whenever Alice cannot follow her strategy, she colours an arbitrary vertex and resumes her strategy for the subsequent rounds. Alice first colours u . Now, Bob can only construct connected blue subgraphs in P or Q since u separates them. For all $1 \leq j \leq m$, whenever Bob colours a vertex in $\{C_j^1, \dots, C_j^6\}$, then Alice also colours a vertex in $\{C_j^1, \dots, C_j^6\}$, so in what follows, we assume that Bob does not colour such a vertex. There are two cases depending on Bob's next move.

Case 1: Bob colours a vertex in Q . Then, Alice colours the vertex x_i that corresponds to the variable x_i she wants to set to true in her winning strategy in ϕ . Now, whenever Bob colours a vertex x_p ($1 \leq p \leq n$ and $p \neq i$), Alice assumes Bob set the variable x_p to false in ϕ and colours the vertex in $\{x_1, \dots, x_n\}$ corresponding to her winning strategy in ϕ . Otherwise, whenever Bob colours a vertex in Q , then Alice colours a vertex in Q . Note that, by this strategy, Alice ensures a connected red subgraph of order at least $\lceil n/2 \rceil + 3m + 1$ since she colours half the variable vertices (rounded up), half the clause vertices, and u ,

and since she followed a winning strategy in ϕ , this subgraph is indeed connected. Furthermore, she ensures that any connected blue subgraph in P is of order at most $\lfloor n/2 \rfloor + 3m$, and hence, Bob must construct his largest connected blue subgraph in Q if he wants to manage a draw. Also note that, if Alice colours v_1 or v_2 she wins, since then she ensures a connected red subgraph of order at least $\lceil n/2 \rceil + 3m + 2$, while she ensures that any connected blue subgraph in Q is of order at most $\lfloor (n + 6m - 2 + 3 - 2)/2 \rfloor + 2 = \lfloor (n - 1)/2 \rfloor + 3m + 2$. Thus, Bob must have coloured v_1 and v_2 in the first two rounds. Now, Alice colours w_2 , and she wins since she ensures that any connected blue subgraph in Q is of order at most $\lfloor (n + 6m - 2 + 2 - 2)/2 \rfloor + 2 = \lfloor n/2 \rfloor + 3m + 1$.

Case 2: Bob colours a vertex in $\{x_1, \dots, x_n\}$. Then, Alice colours w_2 . This forces Bob to colour v_2 , as otherwise, Alice will colour v_2 in the next round and win with the following strategy: whenever Bob colours a vertex

- in $\{w_1, v_1\}$, then Alice colours the other vertex in $\{w_1, v_1\}$;
- y_ℓ , then Alice colours a vertex y_k ($\ell \neq k$);
- x_i ($1 \leq i \leq n$), then Alice colours a vertex x_p ($1 \leq p \leq n$ and $i \neq p$).

In this way, Alice guarantees a connected red subgraph of order at least $\lceil (n + 6m - 2 + n - 3)/2 \rceil + 3 = n + 3m + 1$ without counting any of the vertices C_j^q ($1 \leq q \leq 6$, $1 \leq j \leq m$). Regarding Bob, any connected blue subgraph in P has at most $\lfloor (n - 3)/2 \rfloor + 3 + 3m = \lfloor (n - 1)/2 \rfloor + 3m + 2$ vertices, and any connected blue subgraph in Q has at most $\lfloor (n + 6m - 2 + 2 - 3)/2 \rfloor + 3 = \lfloor (n - 1)/2 \rfloor + 3m + 2$ vertices. Hence, Alice wins in this case, and thus, we can assume Bob colours v_2 . Now, Alice colours w_1 and Bob is forced to colour v_1 for the same reasons as above. Alice now colours y_1 and then she follows the strategy just previously described above (as in the case where Bob did not colour v_2). In this way, Alice ensures a connected red subgraph of order at least $\lceil (n + 6m - 2 + 2 - 2)/2 \rceil + 2 = \lceil n/2 \rceil + 3m + 1$ in Q . Regarding Bob, any connected blue subgraph in P has at most $\lfloor (n - 2)/2 \rfloor + 2 + 3m = \lfloor n/2 \rfloor + 3m + 1$ vertices, and any connected blue subgraph in Q has at most one vertex. Hence, Alice wins in this case as well (recall that n is odd), and this concludes the proof of the first direction.

Now, we prove that if Bob wins in ϕ , then G is AB -draw. We give a drawing strategy for Bob. In what follows, whenever Bob cannot follow his strategy, he colours an arbitrary vertex and resumes his strategy for the subsequent moves of Alice. Part of Bob's strategy is as follows: whenever Alice colours a vertex

- in $\{C_j^1, \dots, C_j^6\}$ for $1 \leq j \leq m$, then Bob also colours a vertex in $\{C_j^1, \dots, C_j^6\}$;
- x_i for $1 \leq i \leq n$, then Bob assumes Alice set x_i to true in ϕ and colours the vertex in $\{x_1, \dots, x_n\}$ corresponding to his winning strategy in ϕ .

So, we just need to give a strategy for Bob in Q' , the subgraph of G induced by $V(Q) \cup \{u\}$. W.l.o.g., we may assume that the first vertex Alice colours in Q' is not v_2 nor w_2 . Bob colours w_2 . If the first two vertices Alice colours in Q' are:

- w_1 and v_1 , then Bob colours u . Now, Alice must colour v_2 , as otherwise, Bob wins as in the proof of the first direction where Alice wins if she manages to

- colour w_2 , v_2 , and u . Then, Bob colours y_k for some $1 \leq k \leq n + 6m - 2$. Now, whenever Alice colours a vertex y_ℓ ($1 \leq \ell \leq n + 6m - 2$), then Bob colours a vertex y_k ($1 \leq k \leq n + 6m - 2$ and $\ell \neq k$);
- w_1 and v_2 , then Bob colours y_ℓ for some $1 \leq \ell \leq n + 6m - 2$. Now, whenever Alice colours a vertex in $\{v_1, u\}$, then Bob colours the other vertex in $\{v_1, u\}$. Otherwise, whenever Alice colours a vertex y_ℓ ($1 \leq \ell \leq n + 6m - 2$), then Bob colours a vertex y_k ($1 \leq k \leq n + 6m - 2$ and $\ell \neq k$);
 - w_1 and u , then Bob colours v_1 . Now, whenever Alice colours a vertex in $\{y_1, \dots, y_{n+6m-2}, v_2\}$, Bob colours another vertex in $\{y_1, \dots, y_{n+6m-2}, v_2\}$;
 - w_1 and y_k for some $1 \leq k \leq n + 6m - 2$, then Bob colours v_2 . Now, Alice must colour u , as otherwise, Bob wins as in the proof of the first direction where Alice wins if she manages to colour w_2 , v_2 , and u . Then, Bob colours v_1 . Now, whenever Alice colours a vertex y_ℓ ($1 \leq \ell \leq n + 6m - 2$), then Bob colours a vertex y_p ($1 \leq p \leq n + 6m - 2$ and $\ell \neq p$);
 - any other combination, then Bob colours w_1 . Now, whenever Alice colours a vertex in $\{y_1, \dots, y_{n+6m-2}, v_1, v_2, u\}$, then Bob colours a different vertex in $\{y_1, \dots, y_{n+6m-2}, v_1, v_2\}$ (note that u is not included here).

In the first two cases above, there is a connected blue component in Q of order at least $\lfloor (n+6m-2+1-2)/2 \rfloor + 2 = \lfloor (n-1)/2 \rfloor + 3m + 1$. In the third case above, there is a connected blue component in Q of order at least $\lfloor (n+6m-2+1)/2 \rfloor + 1 = \lfloor (n-1)/2 \rfloor + 3m + 1$. In the fourth case above, there is a connected blue component in Q of order at least $\lfloor (n+6m-2+2-3)/2 \rfloor + 2 = \lfloor (n-1)/2 \rfloor + 3m + 1$. In the last case above, there is a connected blue component in Q of order at least $\lfloor (n+6m-2+4-4)/2 \rfloor + 2 = \lfloor n/2 \rfloor + 3m + 1 = \lfloor (n-1)/2 \rfloor + 3m + 1$ (since n is odd). To summarise, in each of the cases, Bob has ensured that there is a connected blue component in Q of order at least $\lfloor (n-1)/2 \rfloor + 3m + 1$.

Regarding Alice, in the first two cases above, any connected red component in Q is of order at most $\lceil (n+6m-2+2-3)/2 \rceil + 2 = \lceil (n-1)/2 \rceil + 3m + 1$. In the third case above, any connected red component in Q is of order at most $\lceil (n+6m-2+1-1)/2 \rceil + 1 = \lceil n/2 \rceil + 3m = \lceil (n-1)/2 \rceil + 3m + 1$ (since n is odd). In the fourth case above, any connected red component in Q is of order at most $\lceil (n+6m-2+1-2)/2 \rceil + 2 = \lceil (n-1)/2 \rceil + 3m + 1$. In the last case above, any connected red component in Q is of order at most 1. Thus, in each of the cases, Bob ensured that any connected red component in Q is of order at most $\lceil (n-1)/2 \rceil + 3m + 1 = \lfloor (n-1)/2 \rfloor + 3m + 1$ (since n is odd). Hence, for Alice to win, she must have a connected red component of order at least $\lfloor (n-1)/2 \rfloor + 3m + 2$ in P' , the subgraph of G induced by $V(P) \cup \{u, v_1, v_2\}$ (since, by Bob's strategy, it can never be that u , v_1 , and w_1 (u , v_2 , and w_2 , resp.) are all red). Since Bob follows a winning strategy in ϕ whenever Alice colours a vertex in $\{x_1, \dots, x_n\}$, there is a j for which no vertex in C_j^1, \dots, C_j^6 is adjacent to a red vertex. Thus, any connected red component in P' has order at most $\lceil (n+6m-6)/2 \rceil + 3 = \lceil n/2 \rceil + 3m = \lfloor (n-1)/2 \rfloor + 3m + 1$ (since n is odd). Thus, in G , there is a connected blue component of order at least $\lfloor (n-1)/2 \rfloor + 3m + 1$ and any connected red component has order at most $\lfloor (n-1)/2 \rfloor + 3m + 1$, so Alice does not win in any of the cases. This ends the proof of the second direction. \square

4 Paths and Cycles

In this section, we deal with the case of n -vertex paths $P_n = (v_1, \dots, v_n)$ and cycles $C_n = (v_1, \dots, v_n)$. We begin with two lemmas for specific cases in paths, which we use in the proofs for paths and cycles of odd order. In the following proofs in this section, we often divide the main path P_n into two subpaths Q and Q' , and say that Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.). The way Alice answers to Bob’s moves in Q (in Q' , resp.) is given in the proofs and depends on the different cases. Note that, when following this strategy, Alice may be unable to colour a desired vertex (because Q , resp., Q' , has no uncoloured vertex anymore, or because the desired vertex is already red). In this case, Alice colours an arbitrary uncoloured vertex of P_n . The same applies for when we say that Bob “follows” Alice.

Lemma 1. [2] *For all $n \geq 1$, for the path P_n , Bob has a strategy that ensures that the largest connected red subgraph is of order at most 2, even if one of the path’s vertices of degree 1 is initially coloured red and it is Alice’s turn.*

Lemma 2. [2] *Let $x \geq 1$ and $n \geq x$. For any path P_n with x vertices initially coloured blue, let y be the maximum order of an initial connected blue component.*

- if $y = x$ and, either the blue component contains no ends of P_n or $x = 1$, then, if Alice starts, she has a strategy ensuring that Bob cannot create a connected blue component of order more than $x + 1$;
- otherwise, if Alice starts, she has a strategy ensuring that Bob cannot create a connected blue component of order more than x .

Theorem 5. *For all $n \geq 1$, the path P_n is A-win if and only if $n \in \{1, 3, 5, 7, 9\}$.*

Proof. By Theorem 1, we must prove that P_n is A-win if $n \in \{1, 3, 5, 7, 9\}$, and P_n is AB-draw otherwise. By Theorem 2, P_n is AB-draw if n is even. If $n \leq 9$ is odd, by a case analysis, Alice has a winning strategy that first colours the center of P_n . So, let us assume that $n \geq 11$ is odd. We orient the path from left to right (from v_1 to v_n), so we can use the notions of left and right. We now give a drawing strategy for Bob when $n \geq 11$. Let v_j ($1 \leq j \leq n$) be the first vertex coloured by Alice. Since $n \geq 11$, there are at least 5 vertices to the left or right of v_j , say to the left of v_j , i.e., $5 \leq j \leq n$. Bob colours v_{j-1} . Let $Q = (v_1, \dots, v_{j-1})$ and $Q' = (v_j, \dots, v_n)$. Now, Bob “follows” Alice, that is, when Alice plays in Q (Q' , resp.), Bob then plays in Q (Q' , resp.), and both games are considered independently (since v_{j-1} is blue and v_j is red). Considering Q' as a path with one of its ends initially coloured red, and applying Lemma 1 to it, Bob can ensure that Alice cannot create a connected red component of order more than 2 in Q' . Let v_ℓ be the first vertex that Alice colours in Q . We distinguish two cases:

Case 1: $\ell \neq j - 2$. Bob colours v_{j-2} . Now, whenever Alice plays in Q , while it is possible, Bob colours a neighbour of the connected blue component containing v_{j-1} and v_{j-2} . If it is not possible anymore, either the connected blue component is of order $\lceil (j - 1)/2 \rceil \geq 2$ (in which case the largest connected red component

in Q is of order $\lfloor (j-1)/2 \rfloor$ and so, the game is a draw) or it is of order $2 \leq x < (j-1)/2$ and it is Bob's turn. In the latter case, the connected blue component in Q consists of the vertices v_{j-x}, \dots, v_{j-1} , and v_{j-x-1} is red since Bob cannot colour a neighbour of the connected blue component. Let $R = (v_1, \dots, v_{j-x-1})$ and note that there are exactly x red vertices in R including v_{j-x-1} (one of its ends). Then, applying Lemma 2 to R (but with Bob as the first player), Bob has a strategy ensuring that Alice cannot create a connected red component of order more than x in R . Hence, the game in P_n ends in a draw in this case.

Case 2: $\ell = j-2$. Bob colours v_{j-4} . If Alice colours v_{j-3} , then Bob colours v_{j-5} , and *vice versa*, and this ensures a connected blue component of order at least 2. Otherwise, if Alice colours a vertex v_t with $1 \leq t \leq j-6$, then Bob colours v_{t+1} , unless v_{t+1} is already coloured, in which case, Bob colours v_{t-1} . In the latter case, Bob can ensure a draw since he can ensure that Alice cannot create a connected red component of order more than 2 in $R^* = (v_1, \dots, v_{t-1})$ by Lemma 1. So, assume we are in the former case. Let $R = (v_1, \dots, v_t)$ and $R' = (v_{t+1}, \dots, v_{j-5})$. From now on, Bob “follows” Alice (unless Alice colours v_{j-5} , in which case, Bob colours v_{j-3}), that is, when Alice plays in R (in R' , resp.), Bob then plays in R (in R' , resp.), and both games are considered independently (since v_t is coloured red and v_{t+1} is coloured blue). Considering R as a path with one of its ends initially coloured red, and applying Lemma 1 to it, Bob has a strategy ensuring that Alice cannot create a connected red component of order more than 2 in R . Bob plays in R' assuming that v_{j-5} is already coloured red, and applying Lemma 1 to it, Bob has a strategy ensuring that Alice cannot create a connected red component of order more than 2 in R' . It is easy to see that, in this case, the largest connected blue (red, resp.) subgraph is of order 2 (at most 2, resp.). \square

Now, we address the largest connected subgraph game in cycles. We start with a lemma for a specific case in paths, which we use in the proof for cycles.

Lemma 3. [2] *Let $x \geq 3$, $n \geq x+1$, and $n-x$ be odd. For any path P_n with x vertices, including both ends, initially blue, if Alice starts, then she can ensure that no connected blue component of order more than $x-1$ is created in P_n .*

Theorem 6. *For all $n \geq 3$, the cycle C_n is A-win if and only if n is odd.*

Proof. If n is even, then C_n is a reflection graph, and thus, is AB-draw by Theorem 2. So let n be odd. We describe a winning strategy for Alice. If $n \leq 5$, the result is obvious, so let us assume that $n > 5$. First, let us assume (independently of how this configuration appears) that after $x \geq 3$ rounds, the vertices v_1, \dots, v_x are red, the vertices v_n and v_{x+1} are blue, and any $x-2$ other vertices in $\{v_{x+2}, \dots, v_{n-1}\}$ are blue. Note that it is Alice's turn. By Lemma 3, Alice may ensure that Bob cannot create a connected blue component of order at least x in the subgraph induced by (v_{x+1}, \dots, v_n) . Thus, in this case, Alice wins.

Now, let Alice first colour the vertex v_1 . If Bob does not colour a neighbour of v_1 (say Bob colours v_j with $3 < j < n$, since $n \geq 5$ and odd), then, on her second turn, Alice colours v_2 . Then, while it is possible, Alice colours a neighbour of the

connected red component. When it is not possible anymore, either the connected red component is of order $\lceil n/2 \rceil$ or it is of order at least 3 and we are in the situation of the above paragraph. In both cases, Alice wins.

Therefore, after Alice colours her first vertex (call it v_2), Bob must colour some neighbour of it (say v_1). By induction on the number $t \geq 1$ of rounds, let us assume that the game reaches, after t rounds, a configuration where, for every $1 \leq i \leq t$, vertices v_{2i-1} are coloured blue and vertices v_{2i} are coloured red. If $t = \lfloor n/2 \rfloor$, then Alice finally colours v_n (recall that n is odd) and wins. Otherwise, let Alice colour v_{2t+2} . If Bob then colours v_{2t+1} , then we are back to the previous situation for $t' = t + 1$. Then, eventually, Alice wins by induction on $n - 2t$. If Bob does not colour v_{2t+1} , then Alice colours v_{2t+1} and then continues to grow the connected red component containing v_{2t+1} while possible. When it is not possible anymore, note that removing (or contracting) the vertices v_2 to v_{2t} , we are back to the situation of the first paragraph of this proof (with a connected red component of order at least 3) and, therefore, Alice wins. \square

5 Cographs

For paths and cycles, optimal play depended on positional play with respect to the previously coloured vertices since the graphs are sparse, making it easy for the players to stop the expansion of the opponent's largest connected component. As a consequence, in such cases, players must stop growing their largest connected component, and start growing a new one. Such a strategy is likely to be less viable in denser graphs, in which the game tends to turn into a different one, where the players grow a single connected component each, that they have to keep "alive" for as long as possible. We illustrate this with the case of *cographs*, which leads us to introduce a few more notations (see \mathcal{A}^* below) to describe a linear-time algorithm deciding the outcome of the game in such instances.

A graph G is a cograph if it is P_4 -free, *i.e.*, it does not contain P_4 as an induced subgraph. The class of cographs can be defined recursively as follows. The single-vertex graph K_1 is a cograph. Let G_1 and G_2 be two cographs. Then, the disjoint union $G_1 + G_2$ is a cograph. Moreover, the join $G_1 \oplus G_2$, obtained from $G_1 + G_2$ by adding all the possible edges between the vertices of G_1 and G_2 , is a cograph. Recall that a decomposition, *i.e.*, a sequence of disjoint unions and joins from single vertices, of a cograph can be computed in linear time [6].

To simplify notation in Theorem 7 and its proof, let \mathcal{A}^* be the set of graphs such that there exists a strategy for Alice that ensures a connected red component of order $\lceil |V(G)|/2 \rceil$, regardless of Bob's strategy. *I.e.*, \mathcal{A}^* is the set of graphs in which Alice has a strategy to ensure a single connected red component.

Theorem 7. *Let G be a cograph. There exists a linear-time algorithm that decides whether G is A-win or AB-draw, and whether $G \in \mathcal{A}^*$ or not.*

Proof. The proof is by induction on $n = |V(G)|$. More precisely, we describe a recursive algorithm. If $n = 1$, then G is clearly A-win and $G \in \mathcal{A}^*$.

Let us assume that $n > 1$. There are two cases to be considered. Either $G = G_1 \oplus G_2$ for some cographs G_1 and G_2 , or $G = G_1 + G_2 + \dots, G_m$, where, for every $1 \leq i \leq m$ ($m \geq 2$), G_i is either a single vertex or is a cograph obtained from the join of two other cographs. For every $1 \leq i \leq m$, let us assume by induction that it can be computed in time linear in $|V(G_i)|$, whether G_i is A -win or AB -draw and whether $G_i \in \mathcal{A}^*$ or not. Let us show how to decide if G is A -win or AB -draw, and whether $G \in \mathcal{A}^*$ or not, in constant time.

1. Let us first assume that $G = G_1 \oplus G_2$. We prove that (see [2]):
 - (a) If n is odd, then G is A -win and $G \in \mathcal{A}^*$.
 - (b) If $|V(G_1)|, |V(G_2)| \geq 2$ and n is even, then G is AB -draw and $G \in \mathcal{A}^*$.
 - (c) If $|V(G_1)| = 1$ and n is even, there are two cases to consider:
 - i. If $G_2 \notin \mathcal{A}^*$, then G is A -win and $G \in \mathcal{A}^*$.
 - ii. If $G_2 \in \mathcal{A}^*$, then G is AB -draw and $G \in \mathcal{A}^*$.
2. Now, let us assume that $G = G_1 + G_2 + \dots + G_m$ where, for every $1 \leq i \leq m$ ($m \geq 2$), G_i is either a single vertex or a cograph obtained from the join of two cographs G'_i and G''_i such that $|V(G'_i)| \geq |V(G''_i)|$. Also, let $n_i = |V(G_i)|$ for every $1 \leq i \leq m$, and let us assume that $n_1 \geq n_2 \geq \dots \geq n_m$. To simplify the proof to follow, first note that, if $n_1 = 1$, then G is AB -draw (since $n_2 = 1$ as $m \geq 2$) and $G \in \mathcal{A}^*$ if and only if $G = G_1 + G_2$. Second, if $n_2 = 1$, then the result of the game in G is the same as the result of the game in G_1 , which is known, by Case 1, since G_1 is a join. Moreover, in this case, $G \in \mathcal{A}^*$ if and only if n_1 is odd and $G = G_1 + G_2$. Hence, we may assume that $n_1 > 1$ and $n_2 > 1$. Lastly, in what follows, for any of the winning strategies described for Alice, whenever Bob colours a vertex in G_j for $3 \leq j \leq m$, Alice also colours a vertex in G_j on her next turn. The same holds for any of the drawing strategies for Bob (with Bob and Alice reversed), except for Case 2(e)ii, for which the same only holds for $4 \leq j \leq m$. This guarantees that a player never has a connected component of order more than $\lceil \frac{n_j}{2} \rceil$ in G_j for $3 \leq j \leq m$ ($4 \leq j \leq m$ for Case 2(e)ii). Alice always has a connected red component of order at least $\lceil \frac{n_1}{2} \rceil$ in all of the winning strategies of Alice below, and Bob always has a connected blue component of order at least $\lceil \frac{n_1}{2} \rceil$ in all of the drawing strategies of Bob below. Hence, for all the cases except Case 2(e)ii, we can assume that $G = G_1 + G_2$, and for Case 2(e)ii, we can assume that $G = G_1 + G_2 + G_3$. In what follows, if a player cannot follow their strategy in a round, unless otherwise stated, they colour an arbitrary vertex and then resume their strategy for the subsequent rounds.

There are 5 cases to consider, and recall that we assume that $n_1 > 1$ and $n_2 > 1$, so G''_1 and G''_2 exist. In Case 2(e)iii below, the statement involves n_3 , so if $m = 2$, then we consider that $n_3 = 0$. Also, since Bob always has a strategy where, for each $1 \leq i \leq m$, he colours at least $\lfloor \frac{n_i}{2} \rfloor$ vertices of G_i blue, and since $n_2 > 1$, then $G \notin \mathcal{A}^*$ in all of the following cases. Thus, we just need to show the outcome of the game on G for each case.

- (a) If $n_1 = n_2$, then G is AB -draw.

Assume, w.l.o.g., that Alice first colours a vertex in G_1 . Bob then colours a vertex in G''_2 . Then, whenever Alice colours a vertex in G_1 (G_2 , resp.),

Bob also colours a vertex in G_1 (G_2 , resp.). In particular, if Bob is to colour a vertex in G_2 , then he colours one in G'_2 first if possible, if not, then he colours a vertex in G''_2 , and, if that is not possible, he colours a vertex in G_1 . Similarly, if Bob is to colour a vertex in G_1 by this strategy, but cannot since all of the vertices of G_1 are coloured, then he colours one in G'_2 first if possible, and if not, then he colours a vertex in G''_2 .

If n_1 is odd, then by this strategy, Bob ensures a connected blue component of order $\frac{n_2-1}{2} + 1 = \frac{n_1-1}{2} + 1$ in G_2 and that the largest connected red component in G is of order at most $\frac{n_1-1}{2} + 1$. If n_1 is even, then by this strategy, if Alice colours the last vertex in G_1 , then Bob ensures a connected blue component of order $\lceil \frac{n_2-1}{2} \rceil + 1 = \lceil \frac{n_1-1}{2} \rceil + 1$ in G_2 and that the largest connected red component in G is of order at most $\lceil \frac{n_1-1}{2} \rceil + 1$. If Alice did not colour the last vertex in G_1 , and so, she coloured the last vertex in G_2 , then Bob ensures a connected blue component of order $\lceil \frac{n_2-2}{2} \rceil + 1 = \frac{n_1}{2}$ in G_2 and that the largest connected red component in G is of order at most $\frac{n_1}{2}$. Hence, G is AB -draw.

- (b) If $n_1 > n_2$ and n_1 is odd, then G is A -win.
Alice first colours a vertex in G_1 . Then, whenever Bob colours a vertex in G_1 (G_2 , resp.), Alice colours a vertex in G_1 (G_2 , resp.). By Case 1(a), Alice has a winning strategy in G_1 ensuring a connected red component of order at least $\lceil \frac{n_1}{2} \rceil$. By Case 1, Alice ensures that any connected blue component in G_2 is of order at most $\lceil \frac{n_2}{2} \rceil < \lceil \frac{n_1}{2} \rceil$. Hence, G is A -win.
- (c) If $n_1 > n_2$, n_1 is even, and $|V(G'_1)| \geq 2$, then G is AB -draw.
Whenever Alice colours a vertex in G_1 (G_2 , resp.), Bob also colours a vertex in G_1 (G_2 , resp.). By Case 1(b), Bob has a drawing strategy in G_1 ensuring a connected blue component of order at least $\frac{n_1}{2}$. By Case 1, Bob ensures that any connected red component in G_2 is of order at most $\lceil \frac{n_2}{2} \rceil \leq \frac{n_1}{2}$. Hence, G is AB -draw.
- (d) If $n_1 > n_2$, n_1 is even, $|V(G''_1)| = 1$, and $G'_1 \in \mathcal{A}^*$, then G is AB -draw.
Whenever Alice colours a vertex in G_1 (G_2 , resp.), Bob also colours a vertex in G_1 (G_2 , resp.). By Case 1(c)ii, Bob has a drawing strategy in G_1 ensuring a connected blue component of order at least $\frac{n_1}{2}$. By Case 1, Bob ensures that any connected red component in G_2 is of order at most $\lceil \frac{n_2}{2} \rceil \leq \frac{n_1}{2}$. Hence, G is AB -draw.
- (e) If $n_1 > n_2$, n_1 is even, $|V(G''_1)| = 1$, and $G'_1 \notin \mathcal{A}^*$, then:
 - i. If $n_1 > n_2 + 1$, then G is A -win.
Alice first colours a vertex in G_1 . Then, whenever Bob colours a vertex in G_1 (G_2 , resp.), Alice colours a vertex in G_1 (G_2 , resp.). By Case 1(c)i, Alice ensures a connected red component of order at least $\frac{n_1}{2}$ in G_1 , and that any connected blue component in G_1 is of order less than $\frac{n_1}{2}$. By Case 1, Alice ensures that any connected blue component in G_2 is of order at most $\lceil \frac{n_2}{2} \rceil < \frac{n_1}{2}$. Hence, G is A -win.
 - ii. If $n_1 = n_2 + 1 = n_3 + 1$, then G is AB -draw.
Whenever Alice colours a vertex in G_1 , Bob colours a vertex in G_1 . By Case 1, this ensures that $\frac{n_1}{2}$ of the vertices in G_1 are red and $\frac{n_1}{2}$ are blue. The first time that Alice colours a vertex $v \in V(G_2) \cup$

$V(G_3)$, assume, w.l.o.g., that $v \in V(G_2)$. Bob then colours a vertex in G_3'' . Then, whenever Alice colours a vertex in G_2 (G_3 , resp.), Bob colours a vertex in G_2 (G_3 , resp.). In particular, if Bob is to colour a vertex in G_3 , then he colours one in G_3' first if possible, if not, then he colours a vertex in G_3'' , and, if that is not possible, he colours a vertex in G_2 . As in Case 2(a), Bob ensures a connected blue component of order $\lceil \frac{n_3}{2} \rceil = \frac{n_1}{2}$ in G_3 and that any connected red component in G_2 is of order at most $\lceil \frac{n_2}{2} \rceil = \frac{n_1}{2}$. Hence, G is AB -draw.

iii. If $n_1 = n_2 + 1$ and $n_2 > n_3$, then G is A -win.

Alice first colours the vertex in G_1'' . Then, Alice colours vertices in G_1 as long as she can. By Case 1(c)i, she ensures that any connected blue component in G_1 is of order less than $\frac{n_1}{2}$. If it is Alice's turn, there is a connected red component of order $n_1 - k$ in G_1 for some $0 \leq k \leq \frac{n_1}{2}$, and it is the first round in which she can no longer colour vertices in G_1 , then Bob coloured k vertices in G_1 and $n_1 - 2k$ vertices in G_2 . Then, any connected blue component in G_2 is of order at most $\lceil \frac{n_2 - n_1 + 2k - 1}{2} \rceil + n_1 - 2k = n_1 - k - 1 < n_1 - k$. Hence, G is A -win.

We get the result as a decomposition of a cograph is computed in linear time. \square

6 Further Work

It would be interesting to study the game in other graph classes such as trees and interval graphs. Also, since grids of even order are AB -draw by Theorem 2, it would be intriguing to look at grids of odd order. Just as reflection graphs are a large class of graphs that are AB -draw, another direction would be to find a diverse class of graphs that are A -win. Any graph $G \in \mathcal{A}^*$ of odd order is A -win, and so, perhaps a class of dense graphs of odd order would be a prime candidate.

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Appendix: Omitted proofs

Here, we give proofs that were sketched or omitted in the main part of the paper, due to lack of space. Recall that a full version of the paper is available [2].

Theorem 1. *There does not exist a graph G that is B -win.*

Proof. Towards a contradiction, assume there exists a graph G that is B -win. Consider the following strategy for Alice. In the first round, Alice colours an arbitrary vertex $v \in V(G)$. Now, one vertex is coloured and it can be assumed that Bob is the first player. Alice now plays according to the second player’s winning strategy in G . If, by this strategy, Alice is ever required to colour an already-coloured vertex, then that vertex must be red, and again, in this case, Alice colours an arbitrary uncoloured vertex. Since the only reason a vertex cannot be coloured is that it is already coloured, Alice can always follow this strategy, which is a winning strategy, a contradiction. \square

Theorem 2. *Any reflection graph G is AB -draw.*

Proof. We define a “copying” strategy for Bob which guarantees a draw. Let $U = \{u_1, \dots, u_n\}$ and $V = \{v_1, \dots, v_n\}$ be a partitioning of the vertices of G that satisfies the two conditions required for G to be a reflection graph. Bob’s copying strategy is as follows. In every round, when Alice colours a vertex $u_i \in U$ ($v_i \in V$, resp.), Bob colours its image $v_i \in V$ ($u_i \in U$, resp.). By Bob’s strategy, it is easy to see that Bob can always play in this way. Moreover, by the symmetry of the graph, for every vertex coloured red (blue, resp.) in U , its image is coloured blue (red, resp.) in V . Hence, once all vertices are coloured, by the symmetry of the graph and the second condition for reflection graphs concerning the edges between vertices of U and V , there is a blue isomorphic copy of any connected red subgraph in G . Thus, the game ends in a draw. \square

Theorem 3. *Given a graph G , deciding if G is a reflection graph is GI -hard.*

Proof. The reduction is from the GRAPH ISOMORPHISM problem, in which, given two input graphs G_1 and G_2 , one has to decide whether G_1 and G_2 are isomorphic. We may further assume that G_1 and G_2 are each connected and of odd order, which is one of the input restrictions for which the problem remains hard. Indeed, note that we obtain an equivalent instance of the problem (with the desired properties), upon adding, if needed, one or two universal vertices to both G_1 and G_2 .

We construct a graph H in polynomial time, such that G_1 and G_2 are isomorphic if and only if H is a reflection graph. The graph H we construct is simply $G_1 + G_2$, the disjoint union of G_1 and G_2 . Let us prove the two directions of the equivalence.

First, we prove the forward direction. Assume that the vertices of G_1 and G_2 are u_1, \dots, u_n and v_1, \dots, v_n , respectively, ordered in such a way that there is an isomorphism between G_1 and G_2 where v_i is the image of u_i , for all $1 \leq i \leq n$. Note that no edge joins a vertex from G_1 and a vertex from G_2 . Then, $G_1 \cup G_2 = H$ is a reflection graph with $U = V(G_1)$ and $V = V(G_2)$. The reflection property is trivial in that case.

Now, we prove the other direction. Assume that H is a reflection graph with parts $U = \{u_1, \dots, u_n\}$ and $V = \{v_1, \dots, v_n\}$ such that the function mapping u_i to v_i (for all $1 \leq i \leq n$) is an isomorphism between $H[U]$ and $H[V]$. If U is precisely $V(G_1)$ while V is precisely $V(G_2)$, then we get that $H[U] = G_1$ and $H[V] = G_2$ are isomorphic, by definition of a reflection graph. So, assume this is not the case.

For all $1 \leq i \leq n$, note that either 1) $u_i \in V(G_1)$ and $v_i \in V(G_2)$, 2) $u_i \in V(G_2)$ and $v_i \in V(G_1)$, 3) $u_i, v_i \in V(G_1)$, or 4) $u_i, v_i \in V(G_2)$. We consider all i 's in turn, and possibly switch vertices of U and V as follows:

- If u_i and v_i satisfy Condition 1) above, then we do nothing.
- If u_i and v_i satisfy Condition 2) above, then we move u_i from U to V , and, conversely, move v_i from V to U , resulting in a bipartition of $V(H)$ into two parts U' and V' . Note that, considering the ordering u'_1, \dots, u'_n and v'_1, \dots, v'_n of U' and V' (where $u'_j = u_j$ and $v'_j = v_j$ for all $1 \leq j \leq n$ such that $i \neq j$, and $u'_i = v_i$ and $v'_i = u_i$), respectively, we have that H is also a reflection graph with respect to the two parts U' and V' . Indeed, by the isomorphism and reflection properties, we have that u_i was neighbouring u_{i_1}, \dots, u_{i_k} in U (and so, v_i was neighbouring v_{i_1}, \dots, v_{i_k} in V) and v_{j_1}, \dots, v_{j_k} in V (and so, v_i was neighbouring u_{j_1}, \dots, u_{j_k} in U), which translates, for U' and V' , into u'_i neighbouring v_{j_1}, \dots, v_{j_k} in V' (and so, v'_i neighbouring u_{j_1}, \dots, u_{j_k} in U') and u_{i_1}, \dots, u_{i_k} in U' (and so, v'_i neighbouring v_{i_1}, \dots, v_{i_k} in V').
- If u_i and v_i satisfy Condition 3) or 4) above, then we get a contradiction to one of the original assumptions on G_1 and G_2 . Indeed, assume, w.l.o.g., that u_i and v_i satisfy Condition 3), *i.e.*, both u_i and v_i originate from G_1 . Note that, because G_1 and G_2 are each connected and of odd order, there must be a pair u_j, v_j such that, without loss of generality, $u_j \in V(G_1)$ and $v_j \in V(G_2)$. Furthermore, since G_1 is connected, for such a pair u_j, v_j , it can be assumed, w.l.o.g., that at least one of $u_i u_j$ and $v_i u_j$ is an edge. If

the former edge exists, then the contradiction arises from the fact that, since H is a reflection graph, we must have the edge $v_i v_j$ as well, which is not possible since $v_i \in V(G_1)$ and $v_j \in V(G_2)$. If the latter edge exists, then, because H is a reflection graph, the edge $u_i v_j$ also exists, hence, an edge between G_1 and G_2 , which again is a contradiction.

Once all i 's have been treated this way, H remains a reflection graph, and a direct isomorphism between G_1 and G_2 is deduced. \square

Lemma 1. *For all $n \geq 1$, for the path P_n , Bob has a strategy that ensures that the largest connected red subgraph is of order at most 2, even if one of the path's vertices of degree 1 is initially coloured red and it is Alice's turn.*

Proof. Assume, w.l.o.g., that v_1 is initially coloured red. Whenever Alice colours a vertex v_j with $2 \leq j \leq n$, Bob colours v_{j-1} if it is uncoloured. If v_{j-1} is already coloured, then Bob colours the closest (in terms of its distance in the path) uncoloured vertex that is to the right of v_j . Towards a contradiction, assume that there exist 3 consecutive red vertices, denoted by x_1, x_2, x_3 from left to right in P_n . By Bob's strategy, concerning the 3 vertices x_1, x_2, x_3 , Alice must have coloured x_1 first, then x_2 , and then, x_3 , as otherwise, Bob would have coloured at least one of them. But when Alice colours x_2 , since x_1 is already coloured, then Bob will colour the closest uncoloured vertex to the right of x_2 , which must be x_3 since it is uncoloured as it must get coloured by Alice after she colours x_2 , and thus, we have a contradiction. \square

Lemma 2. *Let $x \geq 1$ and $n \geq x$. Consider any path P_n with x vertices initially coloured blue, and let y be the maximum order of an initial connected blue component.*

- if $y = x$ and, either the blue component contains no ends of P_n or $x = 1$, then, if Alice starts, she has a strategy ensuring that Bob cannot create a connected blue component of order more than $x + 1$;
- otherwise, if Alice starts, she has a strategy ensuring that Bob cannot create a connected blue component of order more than x .

Proof. First, let us consider the case $x = 1$. If $n = 1$, then the result is obvious. We prove the result by induction on n . Without loss of generality, let v_j ($1 \leq j < n$) be the vertex initially coloured blue. Then, Alice first colours v_{j+1} . Let $Q = (v_1, \dots, v_j)$ and $Q' = (v_{j+2}, \dots, v_n)$ (it may be that Q' is empty and/or Q is restricted to one vertex). From now on, Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since v_{j+1} is coloured red). Considering Q as a path with one of its ends initially coloured blue, and applying Lemma 1 to it (but with Bob as the first player), Alice has a strategy ensuring that Bob cannot create a connected blue component of order more than 2 in Q . On the other hand, after the first move of Bob in Q' , it is a path of order less than n with one vertex initially coloured blue and it is the turn of Alice. Thus, by induction (on n), Alice has a strategy ensuring that Bob cannot create a connected blue

component of order more than 2 in Q' . Overall, Alice ensures that the largest connected blue component has order at most $2 = x + 1$. Hence, the claim holds for $x = 1$.

Let $x > 1$ and let us assume by induction that the previous statement holds for all $x' < x$.

- Let us first assume that $y = x > 1$ and the connected blue component B contains no ends of P_n , say $B = (v_i, \dots, v_{i+x-1})$, $1 < i < n - x + 1$. Alice first colours v_{i+x} . If Bob colours v_{i-1} on his next turn (in which case there is a connected blue component of order $x + 1$), then Alice colours $z = v_{i-2}$ (unless $i = 2$, in which case Alice colours an arbitrary uncoloured vertex). Otherwise, Alice colours $z = v_{i-1}$ (in which case the largest connected blue component is of order x). Let $Q = (v_1, \dots, z)$ and $Q' = (v_{i+x+1}, \dots, v_n)$ (it may be that Q and/or Q' are empty, and, in particular, Q is empty if $z \notin \{v_{i-2}, v_{i-1}\}$). From now on, Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since z and v_{i+x} are coloured red). After the first move of Bob in Q (Q' , resp.), it is a path of order less than n with at most $2 \leq x$ vertices initially coloured blue and it is the turn of Alice. Thus, by induction (on n), Alice has a strategy ensuring that Bob cannot create a connected blue component of order more than $x + 1$ in Q (Q' , resp.). Overall, Alice ensures that the largest connected blue component in P_n is of order at most $x + 1$. Hence, the claim holds in this case.
- Next, let us assume that $y = x > 1$ and the connected blue component B contains one end of P_n , i.e., $B = (v_1, \dots, v_x)$. Alice first colours v_{x+1} . Then, Bob colours any vertex in the subpath $Q = (v_{x+2}, \dots, v_n)$. Therefore, Q initially has one blue vertex and it is the turn of Alice. By the base case of the induction ($x = 1$), Alice can ensure that the largest connected blue component in Q is of order at most 2. Overall, the largest connected blue component in P_n is of order at most x . Hence, the claim holds in this case.
- Finally, let us assume that $y < x$. Let (v_i, \dots, v_{i+y-1}) be a largest connected blue component such that there is an initial blue vertex v_j with $j > i + y$. Alice first colours v_{i+y} . Let $Q = (v_1, \dots, v_{i+y-1})$ and $Q' = (v_{i+y+1}, \dots, v_n)$ (it may be that Q and/or Q' is empty). From now on, Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since v_{i+y} is coloured red). After the first move of Bob in Q (Q' , resp.), it is a path of order less than n with at most $y + 1 \leq x$ vertices initially coloured blue (and if there is a connected blue component with x vertices, it must be in Q and it contains the end v_{i+y-1} of the path Q) and it is Alice’s turn. Thus, by induction (on n), Alice has a strategy ensuring that Bob cannot create a connected blue component of order more than x in Q (Q' , resp.). Overall, Alice ensures that the largest connected blue component in P_n is of order at most x . Hence, the claim holds in this case, and in general, since this is the last case. \square

Lemma 3. *Let $x \geq 3$, $n \geq x + 1$, and let $n - x$ be odd. Consider any path P_n with x vertices, including both ends, initially coloured blue. If Alice starts, then*

she has a strategy ensuring that Bob cannot create a connected blue component of order more than $x - 1$ in P_n .

Proof. The first case, $x = 3$, is proven by induction on n . If $n = 4$, the result obviously holds, so assume that $n > 4$ and that the induction holds for all $n' < n$.

- First, assume that the initial blue vertices are v_1, v_2 , and v_n . Then, Alice colours v_3 . Then, Bob colours any uncoloured vertex in $Q = (v_4, \dots, v_n)$. Now, Q has 2 blue vertices (and if there is a connected blue component of order 2 in Q , it contains the end v_n of Q). By Lemma 2, Alice can ensure that Bob cannot create a connected blue component with more than 2 vertices in Q . Overall, Bob cannot create a connected blue component of order at least 3 in P_n .
- Next, let v_1, v_j, v_n (with $2 < j < n - 1$) be the initial blue vertices. W.l.o.g. (up to reversing the path), assume that j is even (note that n is even since $n - x = n - 3$ is odd). Then, Alice colours v_{j+1} . Let $Q = (v_1, \dots, v_j)$ and $Q' = (v_{j+2}, \dots, v_n)$ (it may be that Q' is just the vertex v_n). From now on, Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since v_{j+1} is coloured red). For the game in Q' , applying Lemma 1 (but with Bob as the first player), Alice can ensure the largest connected blue component is of order at most 2 in Q' . For the game in Q , by induction on $n' = |Q| < n$ (note that, because $n' = j$ is even, after the first turn of Bob in Q , the hypotheses hold for $x = 3$ in Q), Alice can ensure the largest connected blue component is of order at most 2 in Q . Overall, Bob cannot create a connected blue component of order at least 3 in P_n .

Now, let us assume that $x > 3$.

First, if there is a connected blue component of order $x - 1$ containing v_1 , then Alice colours v_x , and then she can ensure, by Lemma 1, that Bob cannot create a connected blue component with more than two vertices in (v_{x+1}, \dots, v_n) .

Next, assume that there exists a blue component (v_j, \dots, v_{j+x-3}) of order $x - 2$ not containing any end of P_n . W.l.o.g., let $j - 2 \leq n - j - x + 2$. Alice first colours v_{j-1} . Let $Q = (v_1, \dots, v_{j-2})$ and $Q' = (v_j, \dots, v_n)$. From now on, Alice “follows” Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since v_{j-1} is coloured red). Note that, since $n - x$ is odd and $j - 2 \leq n - j - x + 2$, $Q' = (v_j, \dots, v_n)$ is of order at least $x + 1$. When Bob plays in Q , Alice can ensure, by Lemma 1, that Bob cannot create a connected blue component with more than two vertices in Q . When Bob first plays in Q' , then Q' becomes a path of order at least $x + 1$ with x initial blue vertices, and its largest connected blue component contains its end v_j and is of order at most $x - 1$. By Lemma 2, Alice can ensure that Bob does not create a connected blue component of order more than $x - 1$ in Q' .

Otherwise, there must be an uncoloured vertex v_j such that at most $x - 2$ blue vertices are on the left (on the right, resp.) of v_j . Then, Alice first colours v_j . Let $Q = (v_1, \dots, v_{j-1})$ and $Q' = (v_{j+1}, \dots, v_n)$. From now on, Alice “follows”

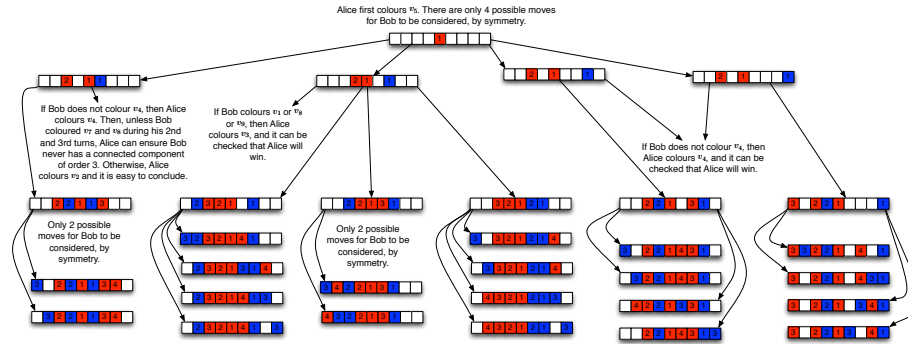


Fig. 2. Winning strategy for Alice in P_9 . The vertices are represented by small squares. A number i in a red (blue, resp.) square indicates that this vertex is the i^{th} vertex coloured by Alice (Bob, resp.). Every arrow corresponds to two moves: first a move of Bob and then of Alice. The leaves of the game-tree correspond to paths where there are still two vertices uncoloured. It is then easy to check the last possibilities.

Bob, that is, when Bob plays in Q (in Q' , resp.), Alice then plays in Q (in Q' , resp.), and both games are considered independently (since v_j is coloured red). By Lemma 2, Alice can ensure, both in Q and Q' , that Bob does not create a blue component with at least x vertices (note that after the first turn of Bob in Q (Q' , resp) it contains at most $x - 1$ blue vertices including at least one of its ends). \square

Theorem 5. *For all $n \geq 1$, the path P_n is A-win if and only if $n \in \{1, 3, 5, 7, 9\}$.*

Missing part of the proof. [Small values of n] We need to show that, if $n \in \{1, 3, 5, 7, 9\}$, then P_n is A-win. It is easy to see that, if $n \leq 7$ and n is odd, then Alice wins by first colouring the center of P_n . If $n = 9$, a winning strategy for Alice is described in Figure 2. \square

Theorem 7. *Let G be a cograph. There exists a linear-time algorithm that decides whether G is A-win or AB-draw, and whether $G \in \mathcal{A}^*$ or not.*

Missing part of the proof. [Case 1] Let us assume that $G = G_1 \oplus G_2$. There are three cases to be distinguished.

1. If n is odd (so we may assume that $|V(G_2)| \geq 2$), then G is A-win and $G \in \mathcal{A}^*$.

Alice first colours a vertex in G_1 . In the second round, Alice colours a vertex in G_2 (it is possible since $|V(G_2)| \geq 2$). Then, Alice colours any uncoloured vertex in each of the remaining rounds. Regardless of Bob's strategy, Alice ends with all the $\lceil \frac{n}{2} \rceil$ red vertices belonging to the same connected component. Since n is odd, G is A-win and $G \in \mathcal{A}^*$.

2. If $|V(G_1)|, |V(G_2)| \geq 2$ and n is even, then G is AB -draw and $G \in \mathcal{A}^*$.
 W.l.o.g., Alice first colours a vertex in G_1 . Then, Bob first colours a vertex in G_1 (it is possible since $|V(G_1)| \geq 2$). In the second round, Bob colours a vertex in G_2 (it is possible since $|V(G_2)| \geq 2$). Then, Bob colours any uncoloured vertex in each of the remaining rounds. Regardless of Alice's strategy, Bob ends with all the $n/2$ blue vertices belonging to the same connected component. Since n is even, Alice cannot have a larger connected red component. Hence, G is AB -draw and $G \in \mathcal{A}^*$.
3. Finally, let us assume that $|V(G_1)| = 1$ (let u be the single vertex of G_1) and n is even (so $|V(G_2)|$ is odd). There are two cases to be considered.
 - (a) If $G_2 \notin \mathcal{A}^*$, then G is A -win and $G \in \mathcal{A}^*$.
 Indeed, Alice first colours u . Then, she plays in G_2 as the second player, and thus, she can ensure that any connected blue component is of order less than $\left\lceil \frac{|V(G_2)|}{2} \right\rceil = \left\lceil \frac{n-1}{2} \right\rceil$ in G_2 since $G_2 \notin \mathcal{A}^*$. Since u is a universal vertex, regardless of Bob's strategy, Alice ensures a connected red component of order $n/2$, and so G is A -win and $G \in \mathcal{A}^*$.
 - (b) If $G_2 \in \mathcal{A}^*$, then G is AB -draw and $G \in \mathcal{A}^*$.
 If Alice first colours a vertex of G_2 , then Bob colours u , and then Bob colours any uncoloured vertex of G_2 in each of the subsequent rounds. Then, Bob ensures a connected blue component of order $n/2$, and so G is AB -draw and $G \in \mathcal{A}^*$.
 Otherwise, if Alice starts by colouring u , then Bob can play as the first player in G_2 and, in doing so, ensure a connected blue component of order $\left\lceil \frac{n-1}{2} \right\rceil = n/2$ in G_2 . Then, again G is AB -draw and $G \in \mathcal{A}^*$. \square